A method of determining the risk of ice deposition due to precipitation and apparatus for exercising the method

The invention relates to a method of determining the risk of ice deposition

5   due to precipitation. The invention is particularly, but not exclusively intended for use in connection with determination of the risk of icing in connection with air traffic.

When there is a risk of ice formation, the air traffic uses anti-icing liquids of

10   various types and concentrations, and the problem is to estimate for how long the anti-icing liquid will stay effective during the existing weather conditions. This is referred to as 'holdover time'; in the following designated 'HOT'.

The international airline organisations publish tables that indicate a time in-

15   terval for holdover time for some anti-icing liquids and for quite a small number of concentrations thereof. These tables, the only tool available at present, are associated with two major factors of uncertainty. Firstly the time intervals listed in the tables are given with large margins, eg a minimum of 30 and a maximum of 60 minutes, and secondly the tables can be used only if it is

20   possible to correctly estimate the precipitation, the tables being divided in accordance with types of precipitation, such as eg snow or super-cooled water. The final responsibility for the estimation lies with the pilot, ie that from within the cockpit, frequently in weather conditions such as following winds and through a heavily heated slanted window, he is to estimate the type of

25   precipitation and then take a stand on the minimum and maximum time intervals given in the table.

The very varying types of precipitation that typically occur within the temperature range of from 5°C and 8°C above freezing point are the cause of the

30   longest delays in the airports and often the planes must wait long to obtain

2

permission to take off, while the anti-icing liquid is consumed more quickly or slowly in response to the precipitation conditions.

5   To date, 141 aircraft accidents have been ascribed to ice accumulation with an ensuing death toll of 1200.

It is the object of the invention to provide a method that enables determination of HOT, wherein the determination is based on actual measurements rather than the subjective estimations resorted to so far in the prior art.

10

This object is accomplished by the method exercised in accordance with the characterising part of claim 1. As it is, a determination of the type of precipitation or the equivalent amount of liquid cannot be taken to express how much ice will be formed, since – by the known methods – it is not possible to distin-
15   guish between super-cooled water and ordinary water. This uncertainty is the greatest precisely within the temperature range where the risk of icing is the largest, viz around 0°C,

By combining the measurements in accordance with the characterising part
20   of claim 1, a complete and objective measurement is accomplished of the conditions that are significant to the estimation of the risk of ice formation when anti-icing liquid is used. The combination and its significance are ex-
plained in further detail in the context of Figures 2 and 3.

25   The two measurements that are combined according to the invention can each be obtained separately by techniques that are already known and that can be performed by use of separate apparatuses or by means of a com-
bined apparatus. For instance, the equivalent amount of liquid can be deter-
mined by means of the technique taught in US patent No. 5 434 778.

30

3

In accordance with a preferred embodiment the actual content of ice in the precipitation is determined by means of a measurement of the actual ice formation, eg by means of the technique taught in WO 00/54078, see claim 6.

5   In accordance with one embodiment the temperature of the surface element is caused to be essentially the temperature of atmospheric air, but alternatively the temperature of the surface element can be controlled to have another predetermined temperature. In this context, parameters such as the temperature of the fuel in the wing or that of the sprayed-on anti-icing liquid
10   may be of relevance.

By the apparatus taught in WO 00/54078, a number of surface elements are rotated at a rate that is to ensure, on the one hand, that the ice is deposited and, on the other, that the majority of water drops are flung off. By exercising
15   the method as recited in claim 10, it is ensured that the slow rotation does not reduce the actual ice formation, and the high rate of rotation ensures that no water remains on the rotor before the amount of ice deposited is weighed. The amount of ice can also be determined in other ways than weighing.

20   Moreover, it is expedient to perform further measurements, eg of the kind featured in claims 11 through 14.

By combining the reliable measurement of the risk of ice formation with knowledge of the type and concentration of the applied anti-icing liquid it is
25   possible to achieve a more reliable estimate of the holdover time, HOT, to be expected for keeping the fly wings free from ice in the given weather conditions. By the invention it is enabled that HOT can be given with a very reduced margin of insecurity compared to the prior art, see the explanation in the context of Figures 2 and 3.
30

However, it often applies – in particular within the field of air traffic – that a rather conservative approach is employed which will undoubtedly involve that some time will elapse before the pilots get used to having access to a well-defined holdover time. Undoubtedly, the well known tables will be consulted for some time yet, of which one of the elements of insecurity was to determine the type of precipitation. By exercising the invention as taught in claim 17, the objective determination that results from the invention can be used to give a reliable indication of the actual composition of the precipitation.

Then the pilots can feel safe in, initially, verifying that the holdover time according to the invention is within the maximum intervals given in the tables and, subsequently, in complete confidence use the holdover time according to the invention as a reliable, well-defined limit.

Safety being, of course, the top priority; there remains also the aspect that the anti-icing liquid is expensive and that it is waste of money and associated with unnecessary pollution to apply more anti-icing liquid than needed to obtain safe flying. By exercising the invention as recited in claim 15 it is possible to determine the smallest requisite concentration of the anti-icing liquid to be applied to accomplish a desired holdover time.

Apart from the above advantages, the invention provides options that present completely new perspectives. By combining measurement equipment for determining the amount of precipitation and combinations with measurement equipment for measuring the amount of ice actually deposited, it is now an option to make a self-learning expert system as recited in claim 19. According to the invention a holdover time is accomplished that is far more reliable than the one used so far, based on measurements, though, of actual weather conditions that applied five or ten minutes ago at most. The known tables are based on empirical conditions that can be registered in a calculation mode with some parameters being automatically adjustable by comparison of the

calculated deposited amount of ice of the calculation model to the amount of ice actually measured. Thereby the risk of ice can be duly predicted. By connecting computers in various airports to each other, and by inputting meteorological data the model can be expanded to provide, based on meteorological data, an estimate of the risk of ice at other airports, and this estimate can be compared to the currently measured ice accumulation at these airports, following which a calculation model can be dynamically optimised.

The invention also relates to an apparatus for exercising the method according to claim 1. The apparatus is characterised by the configuration recited in claim 21.

Preferably the apparatus also contains a data storage with empirical information on holdover time so as to provide a considerably more reliable determination of the actual holdover time, see claim 22.

The apparatus may also feature a computer with a mathematical model for estimating eg holdover time, wherein the model comprises a number of adjustable parameters. By comparing the estimated results to the ones actually measured, as recited in claim 23, the parameters can be adjusted, whereby a self-learning expert model can be accomplished.

The invention also relates to an arrangement as taught in claim 24.

The invention will now be explained in further detail by the description that follows, reference being made to the drawing, wherein

Figure 1 shows a known table used in particular in Canada;

Figure 2 shows a further known table as used ia in Europe;

6

Figure 3 illustrates how HOT is estimated by the prior art;

Figure 4 shows how, according to the invention, time intervals can be given with great accuracy;

5

Figure 5 schematically shows the principle of the invention;

Figure 6 shows an example of the functioning of the calculation unit shown in Figure 5;

10

Figure 7 shows an embodiment of the invention combined with an expert system;

Figure 8 shows the way in which the embodiment shown in Figure 7 works;

15   while

Figure 9 shows how the invention can be combined with meteorological information for predicting the risk of ice, distributed over large distances and periods of time.

20

Figure 1 shows a table, Transport Canada, June 2002, used for estimation of HOT. The table is used "rearwards", ie the pilot estimates visibility in statute miles (the numbers given in the twelve cells). When the visibility in snow is to be estimated it is of significance whether it is light or dark and moreover tem-

25   perature plays a part as well. The table is used for estimating whether the snowfall is 'heavy', 'moderate' or 'light'. Then another table is used (not shown) that indicates intervals for the equivalent amount of water in the precipitation as a function of 'heavy/moderate/light', and once that is found it is possible to resort to a further table (not shown) for obtaining a time interval

30   for HOT as a function of the equivalent amount of water.

7

The method taught in the context of Figure 1 is thus based on an estimate, ia of the visibility and how light or dark it is.

On 29 July 2002 the National Center of Atmospheric Research published an
5   article that explains the scientific reasons why visibility is unsuitable for use as decisive parameter as taught in connection with Figure 1. It follows that this estimate is fairly uncertain.

Figure 2 shows another known table indicating HOT time intervals if one is
10   able to categorize the type of precipitation as one of the six types of precipitation shown in Figure 2. The table can be used for various temperature intervals and for three different mixing ratios for anti-icing liquid.

Figure 3 illustrates the method when the table shown in Figure 2 is used.
15   Figure 3 is made to be, in principle, self-explanatory and hence only few comments will be made to Figure 3. Particular attention is drawn to the fact that in Figure 3 three estimates are made. In connection with information on the current weather being distributed every half hour (METAR), it is necessary, in case of sleet, to estimate whether it is light or heavy sleet. Then this
20   first estimate is converted to an equivalent type of precipitation, being in the example light freezing rain. Use of the table as it is gives a holdover interval of 15-30 minutes (corresponding to Figure 2, top line under the column headed 'light freezing rain'). The upper limit of the time interval is thus given to be twice the lower limit, which is not reassuring. Besides the pilot has to
25   perform the estimate that HOT is to be reduced if the velocity of air or humidity of air is deemed to be high and, finally, the pilot has to estimate how the precipitation may change, if at all.

In practice this means that a pilot who drives for take off, typically in following
30   wind conditions and with heavily slanted and heated window panes, is to be able to determine what the precipitation consists of (water, snow, sleet, su-

8

percooled water, etc). In these conditions the pilot must later queue up for permission to take off and as time goes by perform an estimate whether the anti-icing liquid is still effective, having at his disposal only the very large margins of insecurity shown in Figure 2; in adverse conditions the HOT may

5   be as small as seven minutes. Therefore accidents will occur when the table may indicate HOT to be as much as 30 minutes.

The known measurement equipment for measuring the composition of the precipitation is able to measure drop size and estimate the distribution be-

10   tween snow and water, temperatures, dew point, etc., but is unable to distinguish whether a water drop is super-cooled or not, which is crucial in the estimation of the risk of ice formation.

Reference is now made to Figure 4 that shows a table like the one shown in

15   Figure 2, wherein, however, new measurement parameters are introduced, viz ice factor and equivalent water amount.

It goes without saying that the equivalent amount of water in the precipitation – in combination with the temperature to the left in the table – is very signifi-

20   cant to the amount of anti-icing liquid consumed during a given period of time. Therefore it may be obvious to a person skilled in the art to introduce the equivalent liquid amount into the table and receive information thereon through METAAR every half hour. This time interval is too large, but obviously it is an option to transmit the equivalent liquid amount more often when

25   there is a risk of ice accumulation. However, the other issue is greater, and that is due to the fact that the measurement methods used so far for finding the equivalent water amount has been associated with an inaccuracy of about 30% around 0°C, where the problems solved by the invention are the greatest. The measurement methods known so far have been unable to dis-

30   tinguish between how large a part of the deposited liquid drops are super-cooled and how large a part is not. According to the invention a measure-

9

ment of the actual amount of latent ice content in the precipitation is measure, which is indicated by the numerals 1-9 in Figure 4. The dimension for the ice factor is the weight of deposited ice per surface unit per time unit.

5   By combining ice factor and equivalent amount of water in accordance with the invention it is now possible in a reliable manner to provide far more accurate times/intervals for HOT, as will appear from Figure 4, compared to what could be obtained by the prior art according to Figure 2.

10   If for instance, the table is consulted under heading 'snow' and it is assumed that the ice factor is 2 and the equivalent water amount is between 0.4 and 0.88 mm it is possible to have fairly accurate information on the number of minutes for HOT. However, it is often the case that the actual risk of ice formation (eg at ice factor 2) does not always correlate with the equivalent water 15   amount given in the table, viz 0.4 through 0.8. For instance, it is perceivable that the ice factor is measured to be 5, although the equivalent water amount is measured to be within the range of from 0.4 to 0.8. This is due to the fact that almost all of the precipitation is super-cooled water, and therefore it is an option of one embodiment to select to enter the table under ice factor 5 and 20   disregard the equivalent amount of water that was 0.4-0.8.

Alternatively the ice factor could be measured to be 1, the equivalent water amount being, however, measured to be 0.4-0.8. Albeit the risk of is formation is in this case comparatively lower, there still remains an amount of pre- 25   cipitation, eg snow under 0°C, that would consume a larger amount of anti-icing liquid than would be the case with an ice factor of 1. According to one embodiment the worst possible one of the ice factor measurements or of the equivalent water amount measurement is selected as starting point for the calculation of HOT.

30

The embodiment just described for combination of ice factor and equivalent water amount is a simplified form of utilising the invention. On the basis of the explanations given above, it will be understood that, on the basis of tests, calculations and empirical tables, it will be possible to weight the ice factor

5   and the significance of the equivalent water amount, thereby ensuring that a sufficient amount of anti-icing liquid is applied, while simultaneously use of redundant amounts of anti-icing liquid is avoided.

Table 4 includes some representative minute indicators for HOT. Such val-

10   ues are not merely conditioned by calculations on the basis of said measurements, but also on the safety requirements made by the air traffic authorities.

It is noted that, in accordance with the invention, it is no longer necessary to

15   read out a type of precipitation, and as such distinguish between the various types of precipitation, since the invention enables a fairly accurate value for HOT. The reason why the types of precipitation are still included in Figure 4 is the conservatism that will be discussed at a later point in the specification, and that the types of precipitation can now be determined even more accu-

20   rately by means of the invention (which also correlates with the fact that HOT can be determined more accurately according to the invention).

Figure 5 is a schematic view of an apparatus 1 known per se for measurement of the density of liquid and frozen particles contained in the precipitation

25   and an apparatus 2 for measurement of the actual amount of ice deposited by the precipitation. According to the invention, these measurement results are combined in a calculator unit that is able to produce various output signals such as holdover time, HOT, composition of the precipitation and concentration of anti-icing liquid. The calculator unit receives other parameter

30   values, too, such as empirical values for HOT in response to the composition of precipitation, types of concentration of anti-icing liquid, etc.

As described above, the apparatus for measuring the actual amount of ice in the precipitation could be determined eg by means of the apparatus known from WO 00/540078 that is able to provide an exact result of how much is
5   accumulated on a standard surface element erected on the airport premises. Thereby it can be determined how much of the liquid precipitation is super-cooled, but it cannot be deduced there from how quickly the anti-icing liquid will be consumed since the consumption depends on the type of precipita-tion, see the table shown in Figure 2. Taking one's starting point in the em-
10   pirical tables of holdover time that are based on type of precipitation and combining that with an apparatus for measuring the actual ice formation, it is now possible to determine the type of precipitation with great reliability and therefore the large margins of insecurity of the known tables can be narrowed and in many cases replaced by a certain number of minutes for HOT when
15   the type of concentration of the anti-icing liquid is also entered as a parame-ter in the calculator unit shown in Figure 3.

It is known that a certain degree of conservatism prevails within the aviation industry and it is therefore to be expected that a large number of pilots would
20   prefer to compare the objective and accurate holdover time according to the invention to the teachings of the 'old' tables. As mentioned and as taught by the invention an exact definition of the type of precipitation is also accom-plished and this can also be read out to the pilot who is thereby able able to refer to the 'old' tables.
25

The very high degree of uncertainty that has so far been associated with the prevention of accidents due to ice deposition has, of course, entailed an ex-cess consumption of anti-icing liquid which is both very expensive and also a pollutant. By means of the accurate results accomplished by the invention it
30   is also possible to calculate 'backwards', ie if as a starting parameter it is in-formed to the calculator unit that one needs a holdover time of eg 35 min-

12

utes, the calculator unit is able to produce an output signal that defines the type and concentration of anti-icing liquid. Figure 5 will show a fairly detailed example of the calculation of the requisite type of anti-icing mixture, while simultaneously Figure 5 illustrates how the results from apparatus 1 and ap-
5   paratus 2 are combined.

Figure 5 explains which measurements are typically obtained by apparatus 1 shown in Figure 1. These measurements alone are associated with the draw-back that it is not possible to distinguish between rain and super-cooled rain,
10   but by combining the measurements from apparatus 1 with measurements from an apparatus 2 in accordance with the invention, it is possible to deter-mine the actual amount of ice accumulated, whereby a far more reliable es-timate of HOT is accomplished compared to what was possible with the prior art. It should be noted that the designations 'apparatus 1' and 'apparatus 2'
15   need not necessarily be two physically different apparatuses; rather they ex-press the measurement principles applied and explained in cells 11 and 12, respectively, in Figure 5. It also applies that in case of physical movement apparatus 2 is unable to distinguish between heavy precipitation of very fine snow with small adhesive capability and light precipitation in the form of wet
20   snow with correspondingly large adhesive capabilities; this difference, how-ever, can easily be determined by apparatus 1 on the basis of the difference in reflectivity. The two measurement principles 1 and 2 therefore supplement each other in a particularly advantageous manner for achieving a reliable determination of the type of precipitation, see cell 13. According to a
25   preferred embodiment, the measurements in apparatus 2 are performed at different rates of rotation for the measurement element in order to further en-hance measurement reliability. As it is, an immediate combination of the measurements made by apparatuses 1 and 2 in case of a typical movement of the measurement element does not enable distinction between sleet (wa-
30   ter/snow) and other water and ice-particle mixtures (eg water/hail). This dis-tinction can be obtained by performing measurements in apparatus 2 at a

number of different rates of rotation, whereby the different whirl-off character-
istics of various ice particles and water can be taken into account. The latter
measurements are illustrated in cell 14, such that in cell 15 an even more
reliable determination is obtained of the nature of the precipitation. This was
5   what was the major problem of the prior art when eg the table shown in Fig-
ure 2 was to be used. When the reliable determination of type of precipitation
is combined with the experience numbers shown in cells 16 and 17 it is pos-
sible to obtain a very reliable determination of HOT in cell 18. This very reli-
able determination makes it possible in practice, too, to "calculate rearwards",
10   ie when the very accurate HOT is known in cell 18, it is possible by combina-
tion with the desired durability (cell 19) to deduce that if it is desired to have a
durability of 12 minutes an anti-icing liquid should be in a mixture ratio of 88%
of anti-icing liquid and 12% of water, see cell 20.

15   It is noted that the values given in connection with the figures serve as ex-
amples only, as a complete set of values is very comprehensive and in prac-
tice something that is defined in cooperation with the air traffic authorities.

Figure 6 shows some further advantages of the invention. The calculator unit
20   mentioned in Figure 3 is now a constituent of a larger computer that com-
prises a mathematical model for estimating an expected result. The expected
result was compared in the computer to subsequent actual measurements of
the actual amount of ice formed and in case of a deviation an adjustment is
automatically performed of the parameters of the mathematical model that
25   will, in this manner, become a self-learning expert model. The prerequisite for
this to be accomplished is precisely the combination according to the inven-
tion: viz that a number of reliable measurement results are provided that are
entered into the model and that exact knowledge is provided about the 'true'
result used for performing automatic adjustments of the mathematical model.
30   It will be understood that the apparatus for measurement of the actual
amount of ice can be elaborated on in a variety of ways. For instance it is

14

possible to perform particular procedures on various sequences of rotation and temperature in the apparatus and subsequent measurement of accumulated amount of ice, ice structure, measurement of air resistance, density of the ice, and it is also an option to spray the surface element with anti-icing

5   liquid. In practice, not all of such measurements can be performed immediately before each and every plane is due for application of anti-icing liquid, when the traffic is dense, but these measurements can, when traffic is less dense, contribute to optimisation of the mathematical model, thereby considerably increasing the reliability of the rather short-termed measurements that

10   are performed immediately before anti-icing liquid is applied to a plane.

Figure 7 illustrates how the invention can be used in combination with an expert system. The functions in cells 21-24 are immediately recognizable in view of the above explanations. Thus cell 25 contains the results that can be

15   achieved by means of the combination unit shown in Figure 4 as was explained in the context of Figure 5. Cell 26 contains information on the one hand on the most recently calculated result and previously calculated results and when this is compared to the absolutely most recent result the parameters of an expert model can be optimized such that both yet more well-

20   defined results are obtained in cell 27 and the option is provided of projecting a result eg 20 minutes ahead in time, see cell 28.

In principle, Figure 8 shows how a global network of information relating to the risk of icing can be built. According to the invention the calculations can

25   be supplemented with meteorological information. Figure 8 schematically shows fronts of depressions on their way across the North sea and the computer in one of London's airports 31 now containing exact knowledge of the risk of icing and how it was distributed during passage of the fronts. This information and the meteorological information can be used first in Billund 32

30   and then in Copenhagen 33 where the adjustments that subsequently appear

at the passage of the front can be used at the airport in Stockholm 34 when the fronts pass.

The described considerable improvements in air-traffic safety could not have been obtained by means of a known expert system in combination with the empirical and very uncertain determinations of the risk of icing known so far. The high degree of inaccuracy achieved by the invention enables use of advanced calculation models to impart reliable valued at the individual airports and such that the reliability can be further enhanced by means of measurements performed in other airports.